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Tisova Fire Test – fire behaviours and lessons learnt

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ABSTRACT

One of the largest unknowns in structural fire engineering design is the fire itself, particularly in large internal environments, where real fires have been observed to travel around the floor plate. Several methodologies have been proposed to characterise these fires, most of which rely on the separation of the fire exposure into two so-called fields - near and far – allowing simplifying assumptions to be made. These models are now being used in the structural fire design. However, there is a paucity of validation data for these models with only a few tests reported in the literature. The Tisova Fire Test was conducted on the ground floor of a 4-storey concrete frame building, with concrete and composite deck floors. The fire compartment had a total area of ca. 230m^2, a height of 4.21 – 4.28 m, and a uniform fuel bed across the floor at 40kg/m^2. This paper presents temperatures, spread rate and the observed behaviour of the travelling fire, comparing the current design guidance with the low temperatures observed in the experiment. The paper also examines the experimental issues and the planning of these experiments with a view to helping others plan for and execute large scale fire tests in the future.

KEYWORDS: Travelling fires; full-scale structural fire test; large compartment; fire dynamics; real concrete building; structural fire engineering; lessons learnt

1. INTRODUCTION

Structural fire engineering has taken a huge step forward in the past two decades with greater numbers of buildings benefitting from the application of performance-based design principles to some or all aspects of the structural fire design. This has been enabled by the results of large-scale testing and the lessons learned from the analysis of, for example, the Cardington tests [1] amongst others. Fire engineers are now able to employ sophisticated analysis tools in order to evaluate the structural response of a building to fire, leading to significant cost savings, as well as the contribution of a building structure to the performance-based design of a building for life safety in the event of fire.

One of the largest unknowns in a structural fire design is the fire itself; how and where it might start, how it grows and develops, the intensity of the fire, and how long it will burn for. All of these factors are strongly influenced by the composition and layout of the building under consideration, along with the fuel distribution and relevant ventilation conditions. Historically, the built environment has been largely comprised of spaces configured such that they are likely to lead to ventilation controlled fires, allowing with some degree of confidence the application of fires such as the Eurocode parametric fire or one-zone fire models that assume that the thermal exposure to the structure is relatively uniform throughout the enclosure, i.e. a "well-mixed reactor". This is to a certain extent one of the principle assumptions behind the fire resistance framework [2] which relies on the response of a structure to the "standard fire" scenario as a basis upon which to compare designs, products, safety systems etc. However, this standard fire (e.g. ISO-834 [2]) is only one possible representation of a fire that may occur inside of an enclosure, and may not represent the most onerous (or more realistic) fire exposure that a structure might experience [3].

Over a number of decades architectural trends have evolved and the result is that many buildings in the built environment are now characterised by large open plan areas. The "well-mixed reactor" assumption is not appropriate in these spaces. Indeed, observations of the behaviour of fires in real buildings such as the World Trade centre towers 1, 2 and 7 (2001) [4,5]; the Windsor tower in Madrid (2006) [6]; and the Faculty of Architecture building fire at TU Delft (2008) [7] indicate that in large compartments fires can and do move around floor plates. The well-understood "well-mixed reactor" design fires are therefore not applicable in large area compartments.

Design fires based around the concept of a travelling fire are one possible alternative to the well-mixed reactor assumption. In their most current recognisable form, travelling fires methodologies (developed by Stern-Gottfried & Rein [8] and improved upon by Rackauskaite in 2015 [9] and Dai in 2018 [10]) divide a large compartment into two distinct regions, a near field with localised burning which grows and moves around a floor plate at a rate governed by flame spread and fuel burnout and a far field with pre heating as a result of a developing hot gas layer and then a continued exposure to the hot gas layer after the travelling near field has passed. However, these models are primarily based on analytical and theoretical correlations of the separate phenomena of fire plumes (to characterise the temperature distributions in what is called the far field), flame spread (which are used crudely to characterise the movement of a fire around a floor plate), as well as some assumptions of plume temperatures (to characterise the temperature in the near field). Travelling fire methodologies currently lack the necessary experimental validations that would normally be required before such models are used in industry.

A literature review by Stern-Gottfried and Rein [11] later developed upon by Dai et al [12] present eight known experiments that experiences travelling fires (one of which is the Tisova Fire Test that this paper present greater details of). Other notable large area experiments were also highlighted by Rush and Lange [13]. A selection of these experiments and other pertinent cases are summarised below.

Firstly, Gales identified travelling fire behaviour in a review of the St Lawrence Burns fire tests (117 m^2 & 143.4 m^2) carried out in Canada in (1958) [14], although these experiments only considered temperature at one location within the compartment and with only two thermocouples each. In 1993 a series of nine experiments (127.7 m^2) were conducted at BRE Cardington laboratory in UK [15] with ventilation at only one end of a long narrow compartment. The fire quickly spread in the direction of the available ventilation and then, as the wooden fuel cribs were consumed, burnt back towards the point of ignition. In 1996, the 5th Cardington test (340m^2) [16] exposed a steel frame- composite floor structure to a large open plan fire, however rapid ignition of the 42 wooden fuel cribs meant that the fire grew as opposed to travelled in this well-ventilated fire scenario. In 1999-2000 eight large compartment experiments (144 m^2) were used to validate zone model assumptions under the Natural Fire Safety Concept (NFSC) conducted again at BRE Cardington laboratory in UK [17], however, there was a high temperature non-uniformity experienced in these experiments [18].

Car Park Fire Tests were conducted in 2002 as part of an RFCS project (512 m^2) [19] and saw two tests involving 3 cars each in a test structure with a floor area of 480 m^2. This test is an excellent illustration of near field characteristics in a well-ventilated compartment. Unfortunately, these tests didn't consider far field temperature measurement points, so only near field temperatures were obtained. In 2005 Thomas et al. [20] investigated the fire dynamics in long narrow compartments (16 m^2) with liquid fuel and saw similar response to fire travel and growth as seen in 1993 [15], i.e. burning towards the openings and then slowly retreating back to the point of ignition as the fuel is consumed.

The Veselí Travelling Fire Test (139 m^2), 2011, was the first to use a large single fire crib that was 24 m^2 in area, and was lit to have a fire path parallel rather than perpendicular to the opening [21], near field and far field temperatures were recorded, as well as structural member temperatures. In 2013 a series of experiments were conducted as part of the EPSRC funded 'Real Fires for the Safe Design of Tall Buildings' (RFSDTB) project [22] at the Building Research Establishment (BRE) in UK, where ventilation, fuel load and fuel type were varied to understand the spatial and temporal distribution of temperatures in both the near field and the far field. Several experiments were conducted as part of the RFSDTB project at BRE, including one series with gas burners and another with wood cribs distributed throughout the compartment. In the wood crib experiments, mass loss of the wood cribs was also recorded [23,24]. As a follow up to the RFSDTB tests in BRE, a final test was carried out in Malveira in Portugal, with a continuous fuel bed. This experimental setup was very similar to the previous RFSDTB tests, and was intended as a demonstration test as part of the same project [25]. Both the Veselí and the RFSDTB experiments ignited their cribs in a line presumably to encourage a linear spread of fire over the cribs.

These nine experimental campaigns also vary a great many parameters not listed, such as the amount of ventilation, the height of the compartment, moisture content in the wood. What they all have in common is an attempt to understand and provide data for large floor area fires. This paper presents the results of another experiment with a similar goal – namely the Tisova Fire Test. The aim of this test was to conduct a structurally challenging travelling fire within a large compartment using a uniformly distributed fuel bed (rather than wood cribs). The paper will detail the test set-up and the recorded temperatures within the compartment, highlighting the issues with current design thinking and implications for structural members, but will also highlight issues that occurred during the test that hopefully others can learn from for large compartment fire tests.

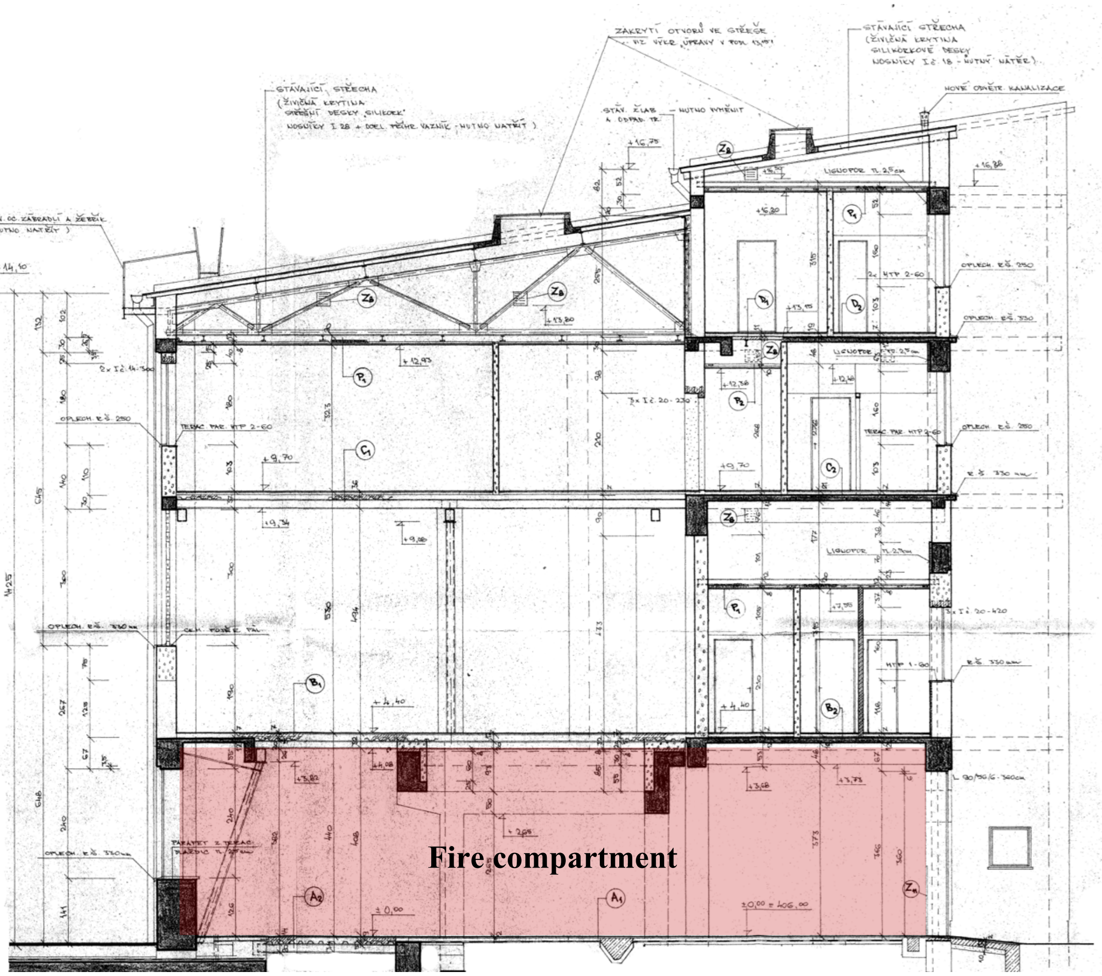
2. THE SETUP OF THE TISOVA FIRE TEST

The Tisova Fire Test was carried out on the 30th of January of 2015, in Tisová, Karlovy Vary of Czech Republic. This work was mainly led by RISE (formerly SP) and the University of Edinburgh, in collaboration with Imperial College London, Luleå Technical University, Technical University of Ostrava, Majaczech, CSTB and CERIB. This fire test was motivated to gather experimental data to help with characterising travelling fires and validating existing or future models used for design [11,12]. *A priori* modelling of the fire was conducted to give the authors a guide to the severity of the fire [26]. Another motivation of the test was to investigate the thermal and structural response of the composite slabs. Furthermore, a post-fire assessment of a structure after a quantified fire event was also performed. The post fire assessment and a description of the thermal and structural response of the composite slabs are planned to be disseminated in future publications. Two reports are also available with more detail on the set-up, results, and modelling of the experiment [27,28], and gas-phase temperature data, additional photos and videos of the fire, and animations of the temperature development are also available [29].

2.1 Test building

The building was constructed in 1958 as a powdered coal boiler and comprised of a reinforced concrete frame and flat slab construction. The two boilers occupied a space which spanned from the ground floor of the building and up to just below the level of the pitched roof. In 1980 the building use was changed, by means of removing the two through-height boilers, with additional floors and slabs added using composite slab construction tied in to the original frame to form a 4-storey office occupancy. The building is shown in Figure 1(a), with a section through the building shown in Figure 1(b). This building was scheduled for demolition, therefore the fire test had the opportunity to be conducted in this real concrete building, on the ground floor, see Figure 1(b).

(a)



(b)

Figure 1(a). Side view of the test building; and Figure 1(b). Blueprint elevation view in year 1980, fire compartment marked with shielded area on the ground floor.

2.2 Fire compartment and fuel load

The ground floor fire compartment was mostly open plan and had a total area of approximately 230 m^2. Its floor to slab soffit distance was 4.28 m under slabs S1 – S4 and 4.21 m for the rest of the structure. It is worth noting that in Figure 2(a), the central lift shaft and machine room as well as the three rooms to the left are not included in the fire compartment. Moreover, as shown in Figure 1(b) and Figure 2(a), four windows were located on the south facing wall, with dimensions 2.4 m in width by 2.4 m in height; three windows were on the east facing wall, with the same dimensions as those on the south facing wall; and one larger window with dimensions 3.6 m in width by 2.4 m in height was on the north facing wall. All windows were removed to ensure the fire was well-ventilated and that a fuel-controlled fire would develop.

Wood cribs were adopted as the fuel load aiming for a natural fire development in the large compartment. Total amount of timber used for the fuel bed was 7 tonnes and this was uniformly distributed covering approximately 170 m^2 of the ground floor area. Figure 2(b) shows the wood cribs distributed as a uniform single fuel bed, apart from a 0.5 m – 1 m path around the perimeter of the floor area, to allow air freely to entrain into the wood cribs. The arrangement of the fuel bed was 5.5 layers of 8 spruce timber sticks per square meter of fuel bed (the 6th layer has 4 sticks hence counted as 0.5 layer). The wood was targeted to be conditioned to 11% moisture content, however found to be between 18-22% after the test. The top of the fuel bed was approximately 40 cm off the floor. Each single wood stick has a cross-sectional size of 0.04 m x

0.06 m and was 1 m in length. 44 sticks per square metre yields a mass density of fuel load 40 kg/m^2, or approximately 680 MJ/m^2 assming the heat of combustion of wood is 17 MJ/kg.

2.3 Instrumentation of the test

2.3.1 Gas-phase temperature

Type-K Inconel sheathed thermocouples of 1.5 mm diameter bead were used to record the spatial temperature histories within the compartment (note: 2.5m sheathed tip, with PVC extensions thereafter). Figure 3(a) shows the installed thermocouple trees, distributed at 56 locations at approximately 2.5 m spacing from each other. Each tree consisted of 9 thermocouples at heights below the slab soffit: 5cm, 35cm, 65cm, 95cm, 140cm, 175 cm, 205cm, 260cm, and 370cm, respectively. Numbering of the thermocouple trees was done according to row and then column, from south to north and from west to east. Thermocouples were attached to stainless steel cables to form the trees which were attached from ceiling to floor, using a nail gun and steel Sabrefix Builders Band (perforated steel band) at the ceiling attachment and I-Shaped pavers blocks to weigh the tree to the floor. The cables from the thermocouple trees were passed up through the first-floor slabs to connect to the data loggers. Where required exposed PVC extensions within the compartment were protected using foil faced ceramic wool high-temperature pipe insulation of 30 mm thickness.

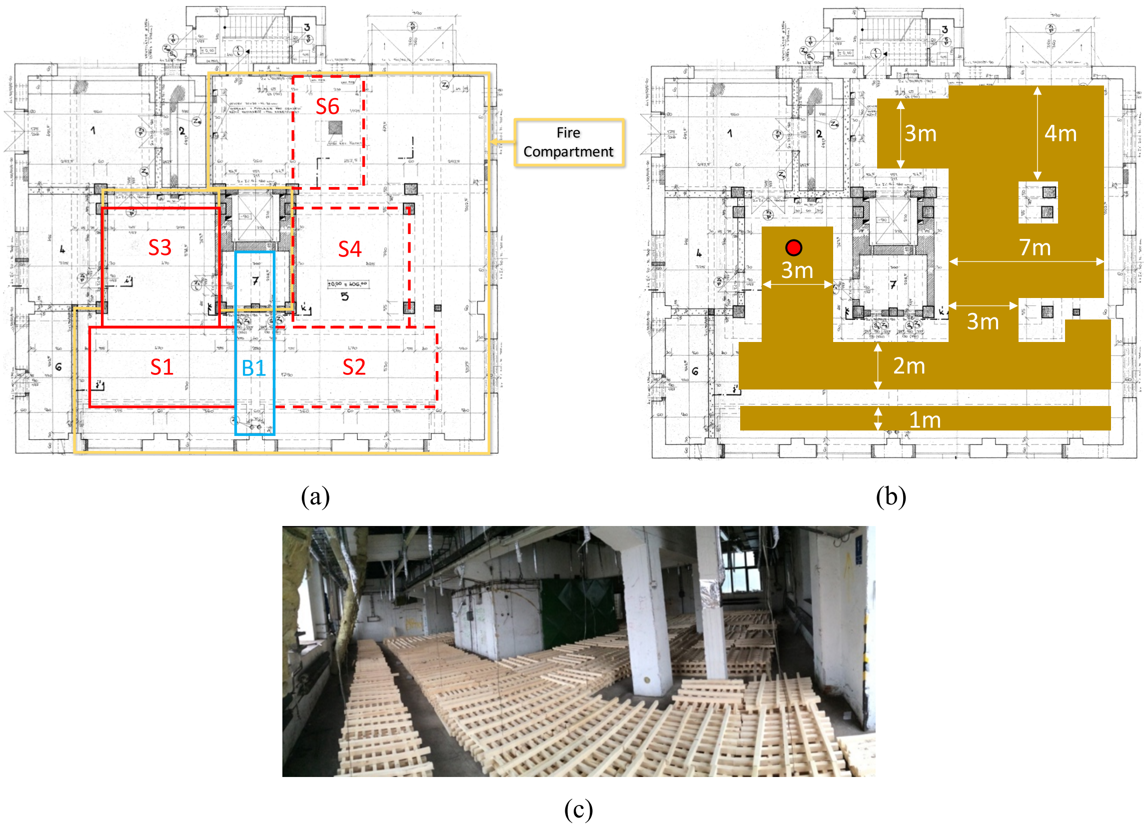
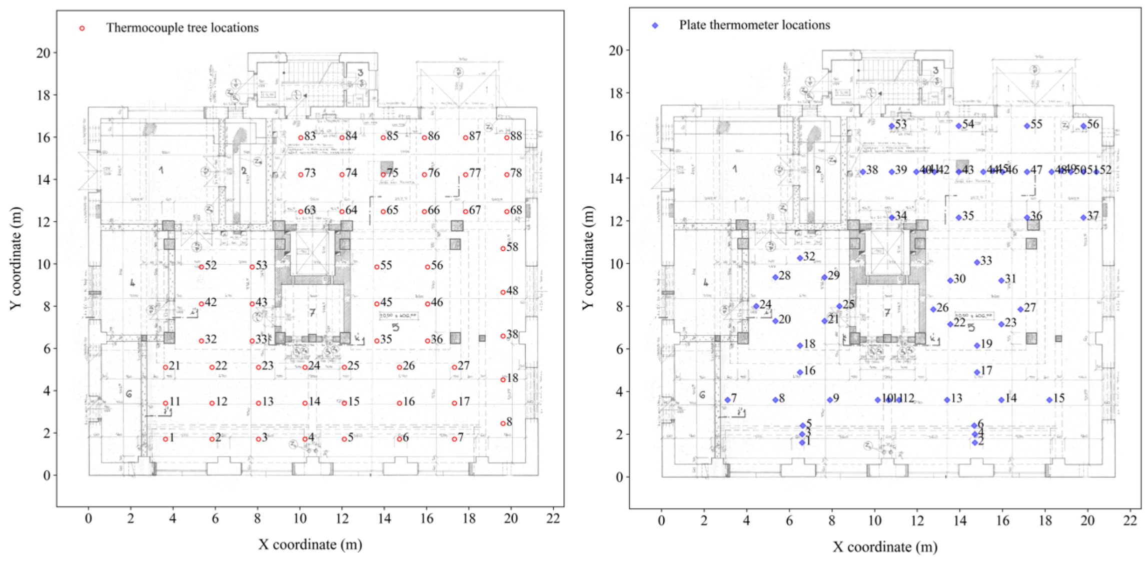


Figure 2(a). Blueprint plan view in year 1980, fire compartment marked with shielded area <u>(i.e. yellow boundary lines)</u> on the ground floor; Figure 2(b). Floor area covered with timber cribs (red dot showing point of ignition); and Figure 2(c). Uniformly distributed wood cribs on site, viewing from the southeast corner of the fire compartment - marked with a red dot in Figure 2(a).

In total 56 plate thermometers were installed within the fire compartment. These were installed facing either down from the soffit of the floor slabs at a distance of 100 mm, or facing away from the vertical side of an adjacent beam at a distance of 300 mm. The distribution of these plate thermometers with corresponding tags through out the compartment is shown in Figure 3(b). Plate thermometers were numbered consecutively by row from the south west corner of the building from west to east.



(a) (b)

Figure 3. Plan layout of the fire compartment marked with instrumented (a) thermocouple trees; and (b) plate thermometers with tags.

2.3.2 Temperature of structural elements

Temperature measurement was also carried out throughout the test at various locations for different types of structural elements, including concrete slabs, composite slabs, concrete beams, and concrete columns. In all of the structural members, the embedded thermocouples comprised a welded Type-K thermocouple, which was inserted in a hole drilled from the upper surface of the structure to the corresponding depth. In the slabs and the beams, the holes were of 12 mm and 16 mm diameter respectively. The holes were backfilled with fast-setting cement. In the reinforced concrete slabs through depth temperature was measured at 4 depths: 20 mm, 40 mm, 60 mm and 80 mm from the fire-exposed soffit of the slabs, which is shown in Figure 4(a). Each of the composite slab had 4 temperature measurement thermocouples at 4 corresponding depths. Two measurements were taken inside each of the troughs of the trapezoidal deck and two were taken outside of the troughs. The position and depth of the recorded temperatures in the cross section relative to the troughs of the composite deck is shown in Figure 4(b). In the majority of the concrete beams, similarly to the concrete slabs, temperature was recorded at approximately 20 mm, 40 mm, 60 mm and 80 mm from the bottom surface of the cross section, in the vertical centreline at the mid-span of the beam. The position of the corresponding thermocouples in the beam cross section is shown in Figure 4(c). In addition to the slabs and the beams, four columns were fully instrumented within the fire compartment. Relevant information and corresponding temperature development in columns during the test, can be found in related publications, e.g. [13].

2.3.3 Other measurements and data logging

Thermocouples on intumescent protected steel plates within the fire compartment, plate thermometers measuring external façade temperatures, deflection gauges on beams and floor slabs, and webcams to supplement the measured data with visual information, were also utilised in the test. Table 1 is a summary of these sensors. Five data loggers were used to record the data. Two Agilent 34980A data loggers were used to record the gas phase temperatures, whilst another Agilent 34980A data logger was used to record structural temperatures. Two Fluke Hydra series data loggers were used to record plate thermometer readings. The logging rate for the Agilent data loggers was approximately 0.1 Hz whilst the Fluke data loggers recorded at approximately 0.2 Hz. The five data loggers were situated within the building on the first floor, above the area unaffected by fire on the ground floor and were connected to external monitoring systems via Ethernet cables.

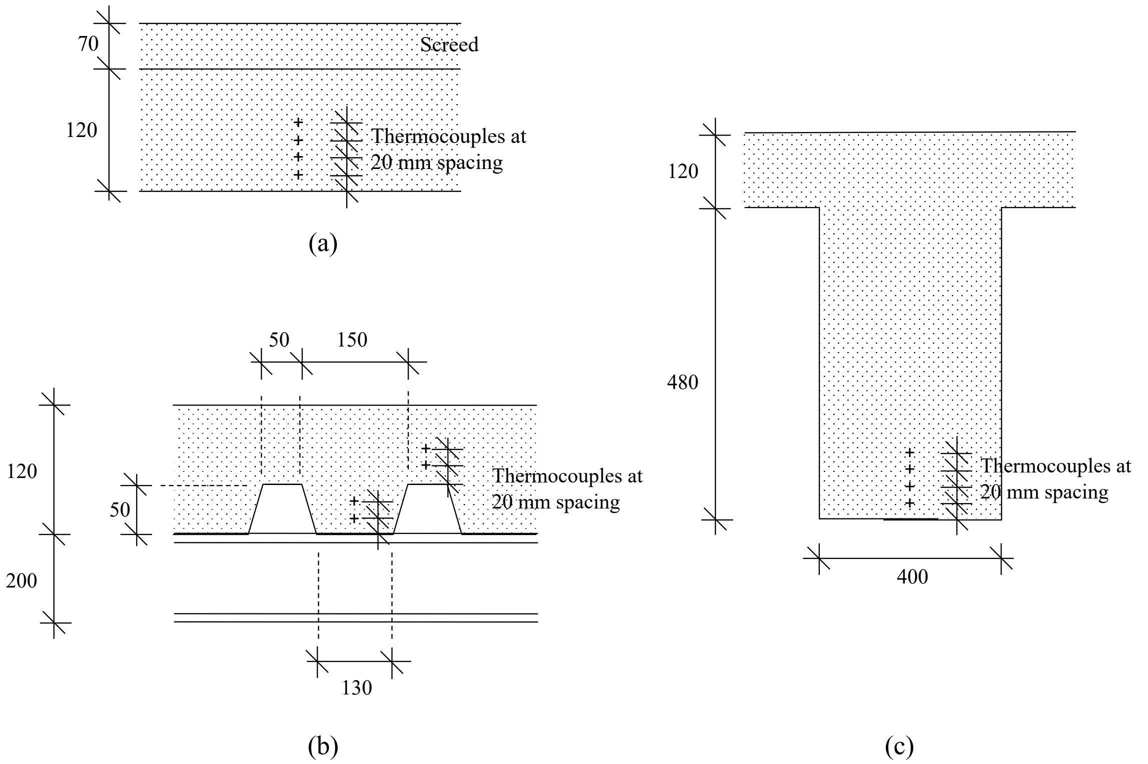


Figure 4(a). Concrete slab; 4(b). Composite slab; and 4(c). Concrete beam with recorded thermocouple positioning, all measurements in mm.

Table 1. Summary of sensors utilised for characterising fire dynamics during the test.

Measurement	**Sensor type**	**Locations**	**Sensor quantities**
Gas-phase temperature	Thermocouple	Within the compartment	504
	Plate thermometer	Adjacent to the structural members	56
External façade temperature	Plate thermometer	At the openings	15
Structural temperature	Thermocouple	In concrete slabs, composite slabs, concrete beams, and concrete columns.	114
Temperature	Thermocouple	On intumescent protected steel plates within the fire compartment	26
Structural displacement	Deflection gauges	On beams and floor slabs	16
Thermal imaging	IR camera	Outside of the compartment	1
Video	Webcams	At the openings	6

3. TEST RESULTS AND DATA ANALYSIS

3.1 Identification of fire modes

In the reporting from the Malveira tests [25], Hidalgo identifies four different modes that can be used to characterise fires in open plan compartments. These modes are based on the ratio of the fire spread rate V_s to the burnout rate V_{BO}. These are:

- Mode 1, which equates to an extremely rapid to instantaneous spread of the fire front such that the fire immediately covers the entire available fuel surface in the compartment. This mode is characterised by a ratio of V_s/V_{BO} >>1. This could be considered a fire mode that leads to a fully developed fire inside of a compartment
- Mode 2, where the ratio of $V_s/V_{BO} > 1$, which corresponds to a growing fire. In this mode the area of fuel that is burning is growing.
- Mode 3, which most closely resembles the travelling fire methodology as defined by Stern-Gottfried and Rein, in which the ratio of $V_s/V_{BO} \approx 1$. In this mode, the burning region does not grow, but rather moves around the compartment.
- Mode 4, which represents burnout of the fire in a large compartment. This is the situation where the burnout of the fuel is occurring faster than new fuel is becoming available or becoming involved in the fire. In this mode, the ratio of $V_s/V_{BO} < 1$.

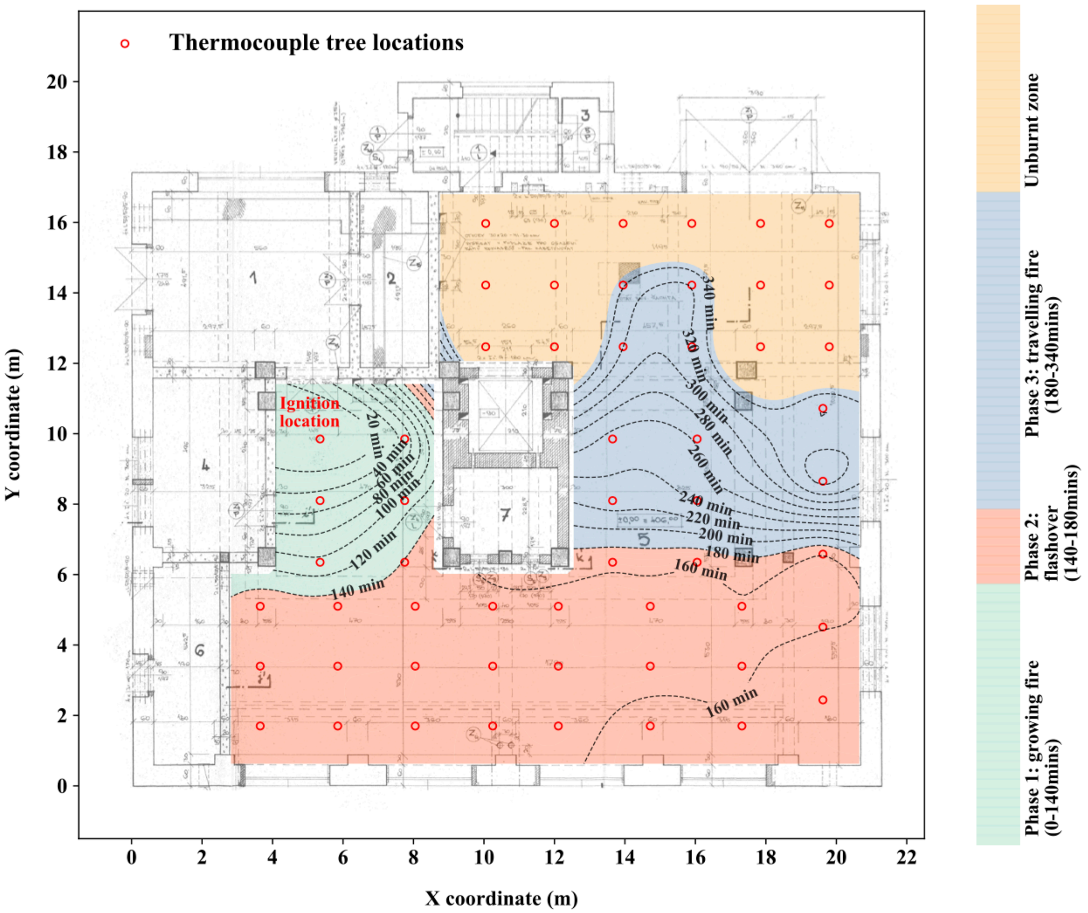


Figure 5: Fire spread leading edge development during the experiment.

All four of these modes are identifiable in the Tisova fire test, lending further support to this characterisation of fires in open plan compartments. This section summarises the fire development as well as the spread and burnout rates in order to demonstrate these modes.

Prior to ignition of the fire, all windows were removed to ensure that the fire was well ventilated and that the burning was fuel load controlled. The fire was ignited with a ‘point’ ignition source, using organic fuel soaked in lighter fluid (no more than 0.02 m^2 in area) within the crib and allowed to spread around the central lift shaft in an anticlockwise direction. Figure 5 shows the fire spread history within the fire compartment, identifying the specific fire spread with time in three general phases. These estimates are based on the thermocouple data near the fuel bed and corresponding visual imaging in the relevant regions.

Based on a combination of thermocouple data and inspection of the webcam data, the burnout time throughout the compartment was estimated. For this analysis, the webcam data turned out to be more useful than the TC data since there is no clear way to associate temperature of TCs on a tree with burnout. The resulting plot of time to burnout throughout the compartment is shown in Figure 6.

In addition, in Figure 5 and Figure 6 the fire compartment area covered in yellow colour, represents the wood cribs not ignited throughout the test.

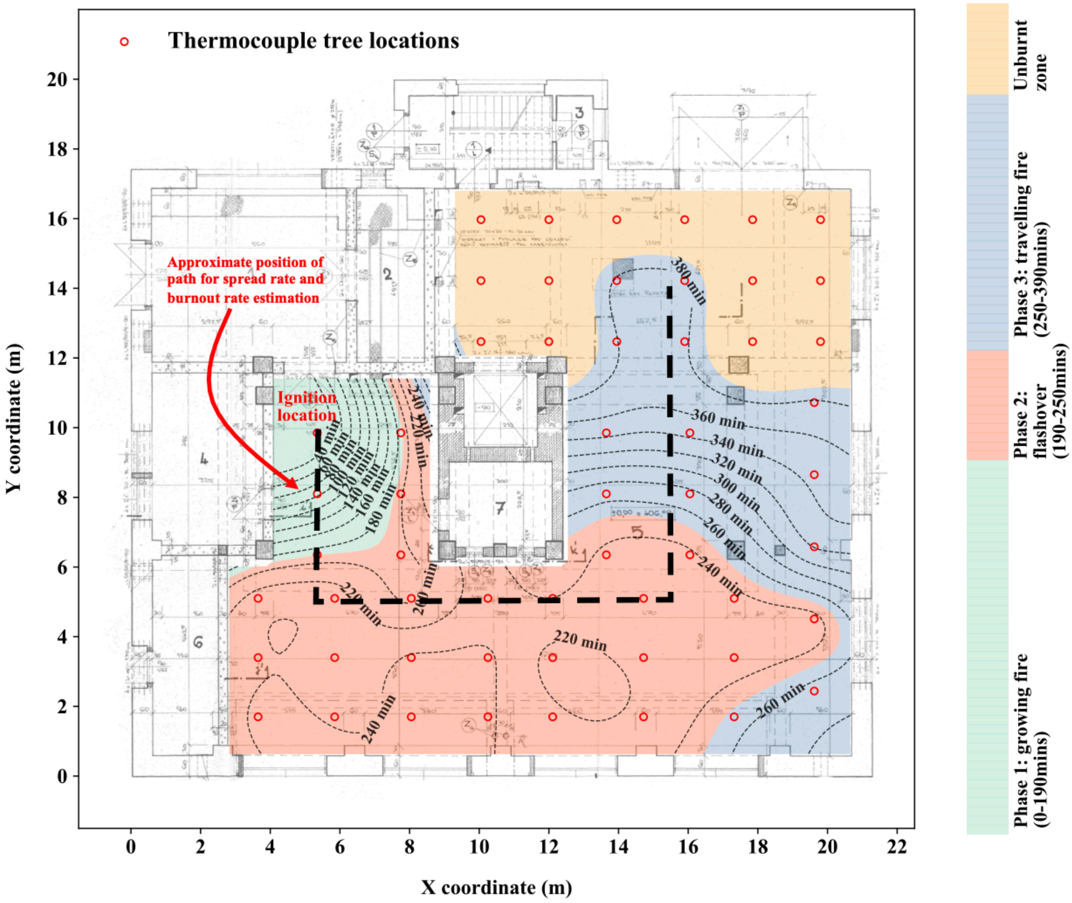


Figure 6: Fire decay trailing edge development during the experiment.

Based on inspection of Figure 5 and Figure 6, the approximate position of the spread rate and the trailing edge of the fire along a path that runs from the ignition location and ends at the end of the burnt region can be estimated at time intervals of 20 minutes. The path passes straight down from the ignition zone to slab S1, then travels east approximately one metre away from the lift machine room of the building and then travels north the same distance from the machine room and the lift shaft. The total length of the path is about 24 metres. The path is also shown in Figure 6. Spread rate and burnout rates are shown in Figure 7. The position of the flame front and the trailing edge are shown in Figure 8. The ratio of spread rate to burnout rate is also plotted in this figure. The shaded regions indicate the modes identified based on the above descriptions. The transition between Mode 2 and Mode 1 is delineated in the figure by a ratio of $V_s/V_{bo} \geq 2$; and the travelling fire, Mode 3, is assumed to occur for $0.7 < V_s/V_{bo} \leq 1.1$. Where there is no trailing edge, i.e. no burnout rate there is no ratio reported since the fire has not yet established.

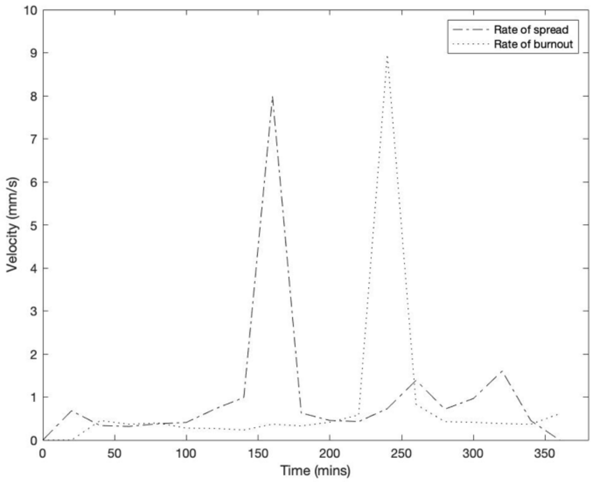


Figure 7: Spread rate and burnout rate as a function of time in the compartment.

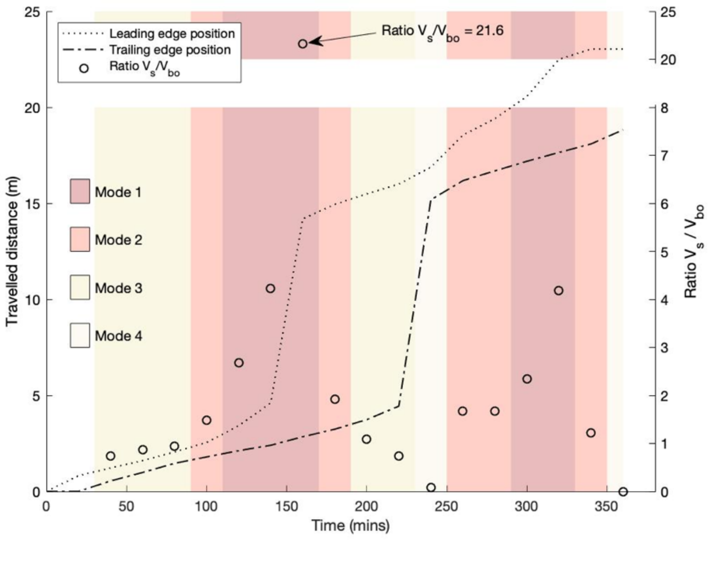


Figure 8: Flame front position, trailing edge position, ratio of spread rate to burnout rate and identification of fire modes in the compartment.

Mode 3 occurs in the compartment from 0 min to approximately 80 mins. Over this period the fire was successfully ignited within one wood crib as planned and grew slowly underneath the area under slab S3. The flame length along the path was less than 1 m after around 80 mins, and the corresponding flame height was between 1.5 m – 2 m according to post-test analysis of the webcam recordings. The resulting temperatures in the compartment, especially near the ceiling, were not high enough for a structurally challenging fire, being well below 200 °C (The details of gas-phase temperature development are discussed in the subsequent section 3.2). To encourage the fire growth during the test, the ventilation was reduced by replacing all of the windows at around 100 mins into the test. This increased the fire spread rate to some extent, with the flame width growing to approximately 2 m from 100 mins to 140 mins. The transition from Mode 3 to Mode 2 occurred after approximately 100 minutes, indicating this slowly growing fire as more heat was retained within the compartment.

Note the flame spread and burnout rates over this period, as shown in Figure 7. Once established, these are approximately equal at ca. 0.5 mm/s, up until the time that the windows were replaced, at which point the burnout rate decreases slightly and the flame spread rate increases slightly up until 140 mins. This gradual fire spread rate acceleration is because more heat was generated as the fire was developing, which in turn aided the fire development and its spread rate.

To ensure the fire development could generate a structurally challenging fire, a 10-litre mixture of gasoline and diesel at a ratio of 1:1 was distributed over the fuel bed along the perimeter of the southern part of the compartment (i.e. roughly the area covered in pink colour at Phase 2 shown in Figure 5) at around 150 mins. This mixture added very little to the fuel load to this area, however this accelerant significantly increased the flame spread rate over this part of the compartment. It can be seen from Figure 5 that fire rapidly spread over the entire south part of the compartment from 140 mins to 180 mins, with a roughly straight-line distance of 18 m, with an averaged fire spread rate of 3.2 mm/s, based on the spread rate shown in Figure 7. This transition to Mode 1 is clear from the ratios of spread rate to burnout rate, as well as the rapid spread of the flame front in Figure 8 while the trailing edge travels at the same rate. Spread rate increased dramatically over this time, peaking at ca. 8 mm/s. Burnout rate however remains relatively constant.

At approximately 180 mins the fire transitions to a Mode 2 fire. This corresponds with a reduction in the spread rate but not the burnout rate. The ratio of the two remains above 1. After 210 minutes the burnout rate accelerates, peaking at 9 mm/s and the fire transitions to Mode 4, i.e. a decaying fire. This is followed by a subsequent regrowth in the fire and a transition back to Mode 2 after 250 minutes, with flame spread rate again increasing up to 1.5 mm/s while burnout rate decreases again to 0.5 mm/s. This regrowth is almost certainly attributable to the change in geometry and ventilation conditions for the fire as it moved away from the 4 windows at the south of the compartment and the wide-open area beneath slabs S1 and S2 to the less well ventilated and more enclosed space underneath slab S4. This highlights the importance of the geometry in determining fire behaviour, even for fires in such open plan enclosures. The fire almost transitions back to Mode 1 after 320 mins. However, the fire finally enters Mode 4 again and decays, spread rate drops to 0 mm/s and burnout rate increases, going out at approximately 340 mins.

3.2 Gas-phase temperature

To fully understand the thermal impact on the structural elements within the large test compartment, gas-phase temperature is investigated through utilising the thermocouple raw data with sequential contour plots. However, due to the long duration of the test (i.e. 6 hours) and insufficient protection around the PVC insulated extensions, the complexity of the fire (i.e. the transition between many different fire modes), and some internal fittings falling into thermocouple trees, a large amount of thermocouples were damaged during the process of the test. Hence the data validity of these thermocouples within the compartment should be first examined.

3.2.1 Broken thermocouples

Up to 200 mins of the test, majority of the TCs were intact according to Figure 9(a). Except for minor percentage of the TC trees located at the 'transition' area from the Mode 2 to the Mode 1 fire started at around 140 mins. The TCs at this transition area suffered the most severe and the longest fire impact duration, which is confirmed by Figure 9(b) at 360 mins. Hence, as shown in Figure 10, TCs at Slice 1 (in red) up to 200 mins, and Slice 2 (in yellow), Slice 3 (in blue), Slice 4 (in green) up to 360 mins, are to be analysed in the subsequent section. In the elevational dimension, all those slices are related to the distance from the floor to the ceiling level.

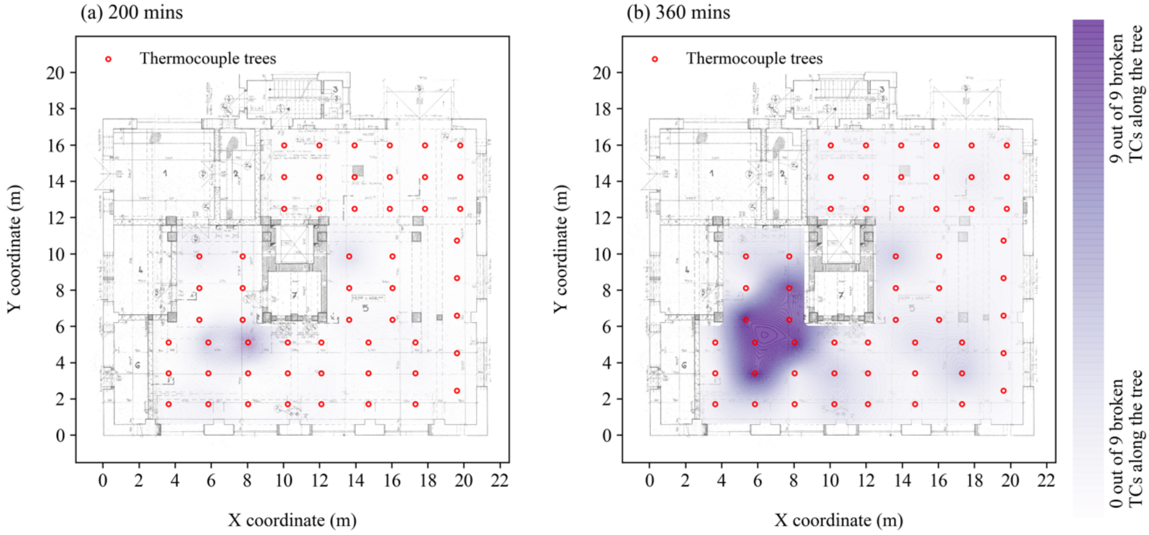


Figure 9: Percentage of the broken thermocouples (TCs) along each TC tree during the test (each tree contains 9 TCs), darker colour indicates majority of the TCs along that TC tree were broken. (a) broken TC percentage contour at 200 mins; and (b) broken TC percentage contour at 360 mins.

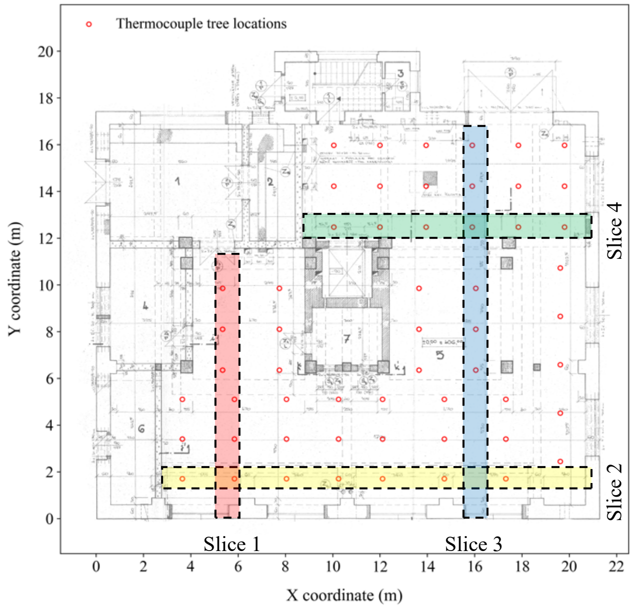


Figure 10. TCs chosen to be analysed based on Figure 9, Slice 1(in red) is analysed up to 200 mins, and Slice 2 (in yellow) & Slice 3 (in blue) & Slice 4 (in green) are analysed up to 360 mins.

Figure 11. Images taken at the front face of the compartment at (a) 4 mins, (b) 98 mins, (d) 152 mins, and (e) 198 mins; image taken at the back face of the compartment at (f) 200 mins; images taken at the side face of the compartment at (c) 149 mins, (g) 242 mins (marked red circle explained in section 3.2.3), (h) 364 mins. ('Slices' with perspective effect marked in photos, the corresponding 'Slices' location can be found in Figure 10 under plan view)

3.2.2 Fire development at Slice 1

The fire was successfully ignited as planned with a point source, forming a localised heating at the beginning of the fire test, as shown in Figure 11 (a) and Figure 12 (a). However, it took around 100 mins for the fire to spread 2.5 m from the origin with a very low flame height around 1m, as shown in Figure 11 (b). Besides, Figure 12 (b) suggests that gas phase temperatures were from 50 ºC to 150 ºC, which was not a structurally challenging fire as was intended. At around 150 mins, the fire was accelerated with diesel and gasoline, and the Mode 1 fire started to impact the structures with temperatures as high as 650 ºC, as shown in Figure 11 (d) & (e), and Figure 12 (c) & (d). If the area between the flame spread front and the trailing edge could be regarded as the 'near-field' under the travelling fire concept, it could be seen that the temperature distribution at the 'far-field' (i.e. post-fire region) are generally uniform through the space, ranging from 250 ºC to 350 ºC in Figure 12 (c) and (d). Moreover, temperature near the opening region is usually lower due to the cold air entrained in the compartment through the windows, as suggested by all the subplots in Figure 12.

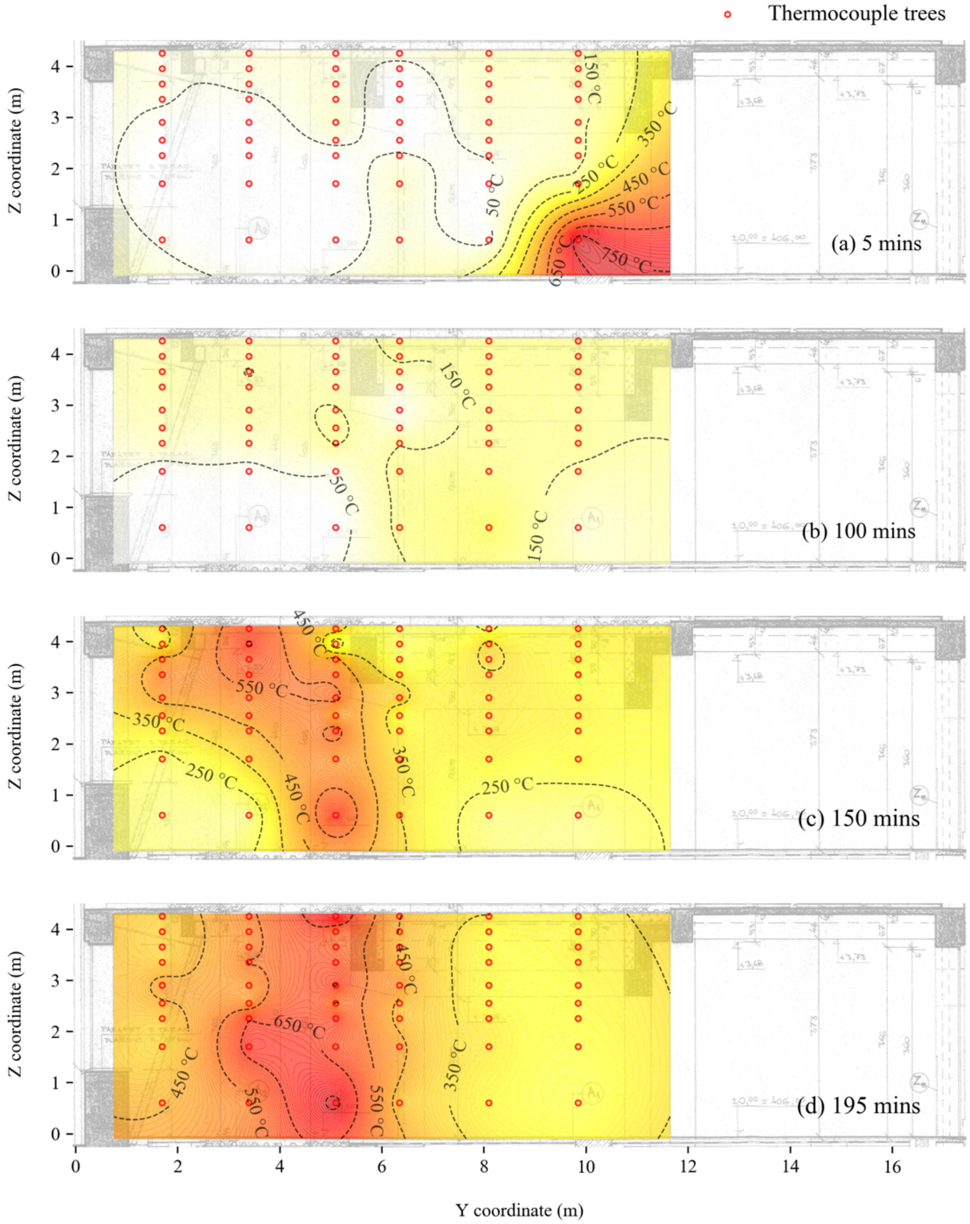


Figure 12. Temperature development in elevation view at Slice 1 (see Figure 10), at (a) 5 mins, (b) 100 mins, (c) 150 mins, and (d) 195 mins respectively.

3.2.3 Fire development at Slice 2

Figure 11 (c) and Figure 13 (a) illustrates the smoke accumulation upon the whole ceiling at around 135 - 150 mins, which formed a two-zone distinct temperature distribution through the regions full 18 m length. In addition, similar two-zone fire dynamics were also identified in another fire experiment in a full-scale open floor plan enclosure, performed by Hidalgo *et al.* in 2013 [24]. It was found that the smoke layer depth was nearly constant through the full 17.8 m length of the test compartment. In Figure 11 (f) and Figure 13 (b) at around 200 mins, it suggests that the temperature was uniformly distributed throughout the whole space from 350 ºC to 450 ºC, after the Mode 1 fire occurred. Moreover, as shown in Figure 13 (c), the temperature near the fuel bed was around 400 ºC, which was higher than the temperatures near the ceiling level at around 300 ºC. This is mainly because the 'burnt' fuel bed remained hot and less affected by the cold air through the openings due to the sill height, which was marked with a red circle in Figure 11 (g) for emphasis. Figure 13 (d) illustrates the temperature distribution at the end of the test.

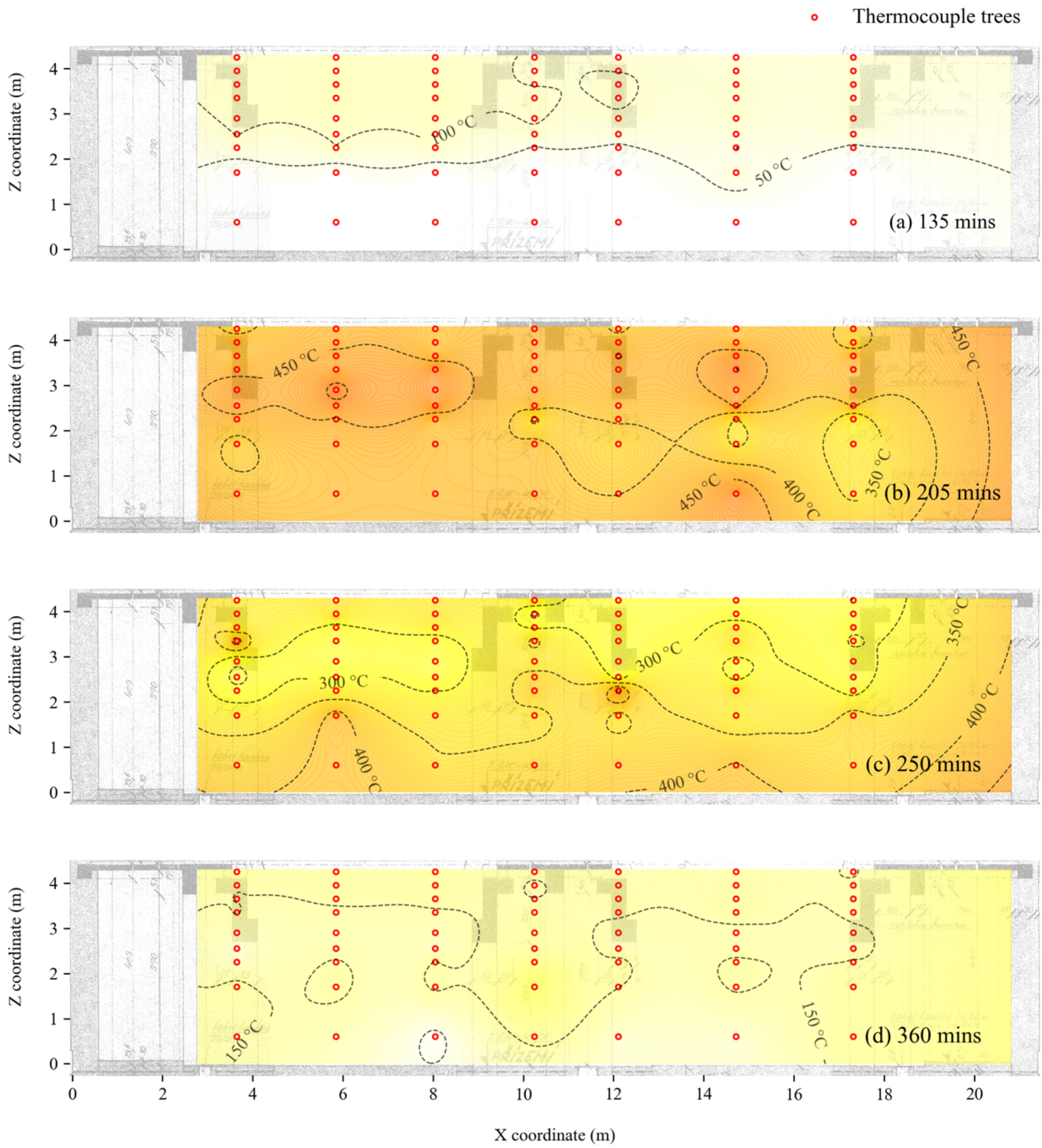


Figure 13. Temperature development in elevation view at Slice 2 (see Figure 10), at (a) 135 mins, (b) 205 mins, (c) 250 mins, and (d) 360 mins respectively.

3.2.4 Fire development at Slice 3

The subplots of Figure 14 well present the near-field of the 'travelling' fire nature in this test. Before the Mode 1 fire stage (i.e. during the Mode 2 and the Mode 3 behaviour), far-field smoke uniformly accumulated upon the entire ceiling along the 18m length, even the temperature was relatively low between 50 ºC - 100 ºC as shown in Figure 14 (a) and confirmed by Figure 11 (c). It is worth noting that the only 'turbulent' part of the smoke in this figure is due to the existence of the down-stand beams, which are marked with red circles in Figure 14 (a). As suggested by Figure 14 (b), when the transition to Mode 1 fire occurred, 'near-field' was with relatively uniform high temperature between 400 ºC - 500 ºC. 'Far-field' is fully engulfed with smoke at around 250 ºC. In Figure 14 (c), after the Mode 1 fire transitioned back to Mode 2, 'near-field' travelled further with higher temperature at the bottom and lower at the top. 'Far-field' remained with accumulated full height smoke at around 200 ºC.

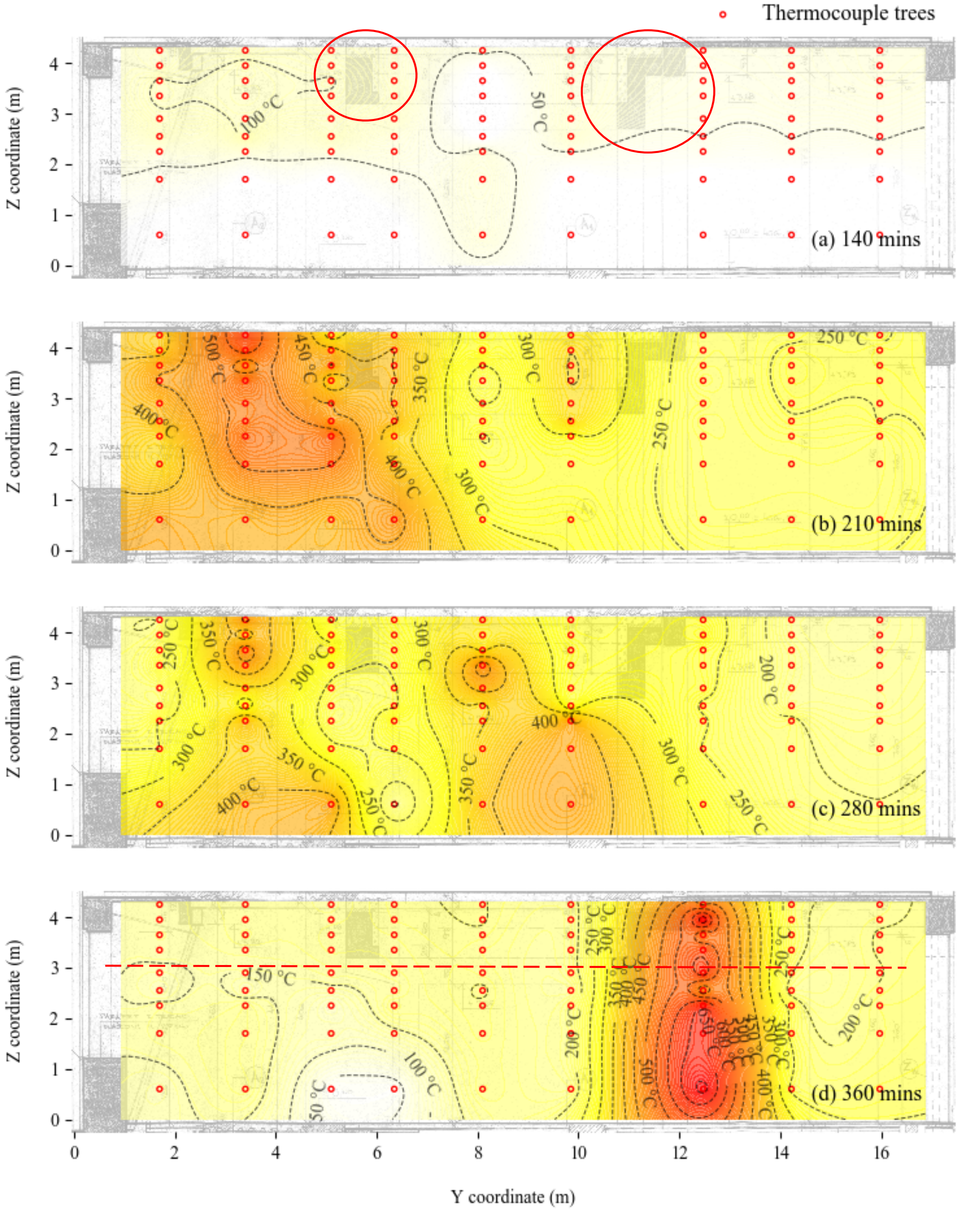


Figure 14. Temperature development in elevation view at Slice 3 (see Figure 10), at (a) 140 mins, (b) 210 mins, (c) 280 mins, and (d) 360 mins respectively.

At around 360 mins in Figure 14 (d), 'near-field' travelled even further. It is interesting to note that the full-height accumulated smoke was again relatively uniform through the compartment between 150 ºC - 200 ºC, which is marked with a straight in both Figure 14 (d) (based on rough estimate at 150 ºC) and Figure 11 (h) (based on observation from the webcam recordings).

3.2.5 Fire development at Slice 4

The subplots of Figure 15 well illustrate the far-field of the 'travelling' fire nature in this test. When the transition to Mode 1 fire occured, 'far-field' smoke started to accumulate with more layer height and tended to transition from a two-zone to a one-zone temperature distribution, as shown in Figure 15 (a). At 180 mins, 'far-field' smoke continued to accumulate at the far end, and temperature distribution was transiently affected by the down-stand beams marked with a red circle in Figure 15 (b). At the Mode 1 fire stage at 200 mins, 'far-field' remained with accumulated full height smoke at around 250 ºC shown in Figure 15 (c). At last, in Figure 15 (d), 'near-field' travelled to the far end of the compartment.

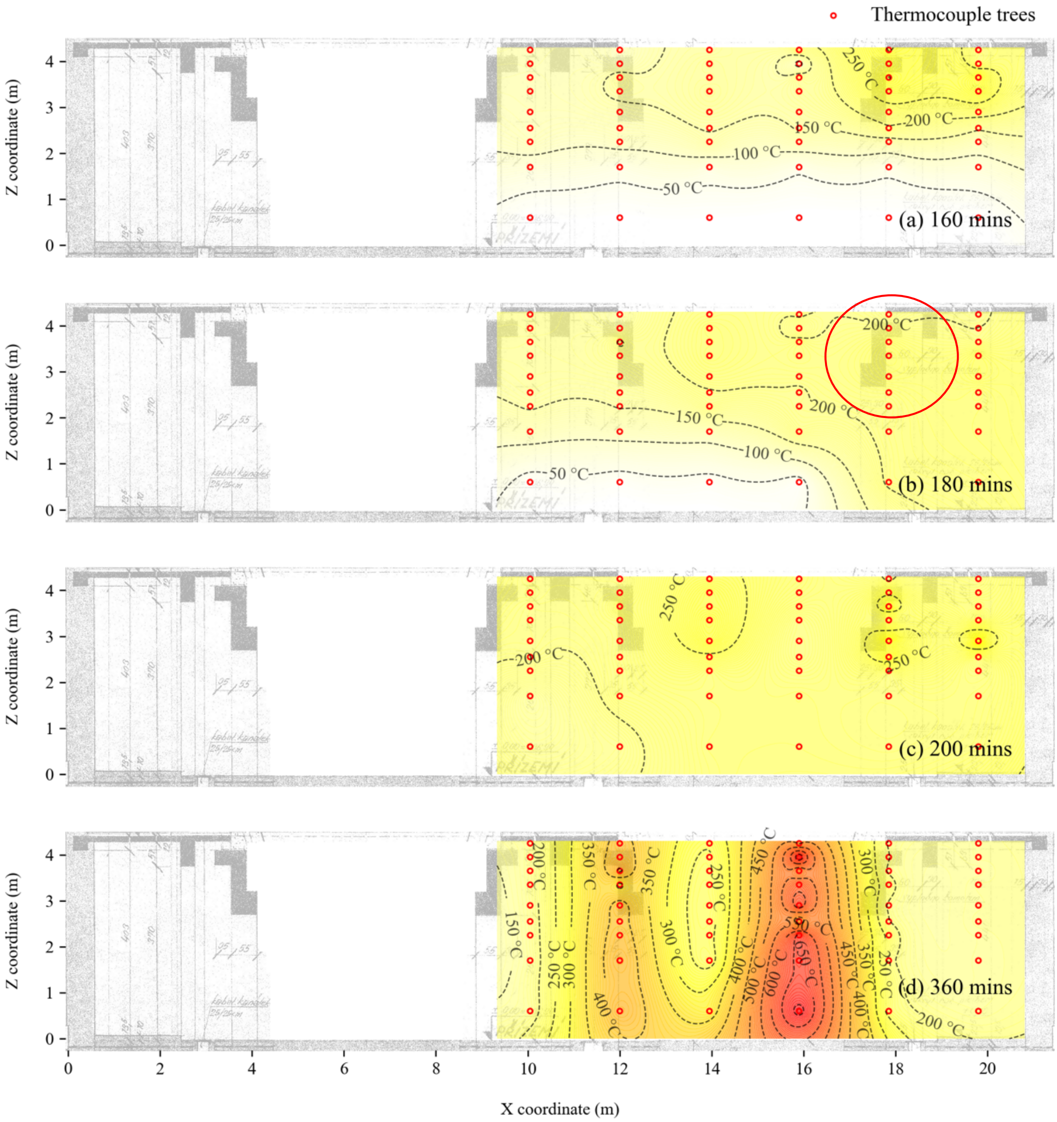


Figure 15. Temperature development in elevation view at Slice 4 (see Figure 10), at (a) 160 mins, (b) 180 mins, (c) 200 mins, and (d) 360 mins respectively.

3.3 Thermocouple temperatures at selected locations

To further exploit the development of thermal environment within the large compartment, Figure 16 presents the thermocouple (TC) temperature evolution at selected locations. Figure 16 (a) illustrates a drastic temperature difference through the compartment height near the fire ignition location (TC tree 52, see Figure 3) at the beginning of the fire (from 0 min to 30 mins), where the thermocouple near the fuel bed (i.e. at 370 cm) had a temperature as high as to 900 ºC, compared to with the ones near the ceiling well below 200 ºC. After 30 mins, this difference diminished with similar temperatures ranging from 100 ºC - 200 ºC. A sudden increase of temperature up to 400 ºC happened at around 150 mins, due to the onset of the Mode 1 fire phase. After this short period all thermocouples through the full height of the compartment had roughly similar temperatures, which confirmed the findings in Figure 12 (d). It is worth noting that from 150 mins to 210 mins, the initial peak was the accelerant burning off and the subsequent gradual increase was as the hot gasses accumulated due to the increased spread rate of the flame front. The temperatures then started to decrease as the spread rate decreased In Figure 16 (b), it can be clearly seen that the temperature of the thermocouples near the openings (i.e. at 205 cm and 260 cm) were lower compared with temperatures of other ones on tree 2, from 0 min to 150 mins. This is because the cold air freely entrained through the windows which lowered down the compartment temperature locally. Note that the higher temperatures of the thermocouple at 140 cm between 160 mins to 210 mins is due to localised burning of a cable that was dislodged from the ceiling.

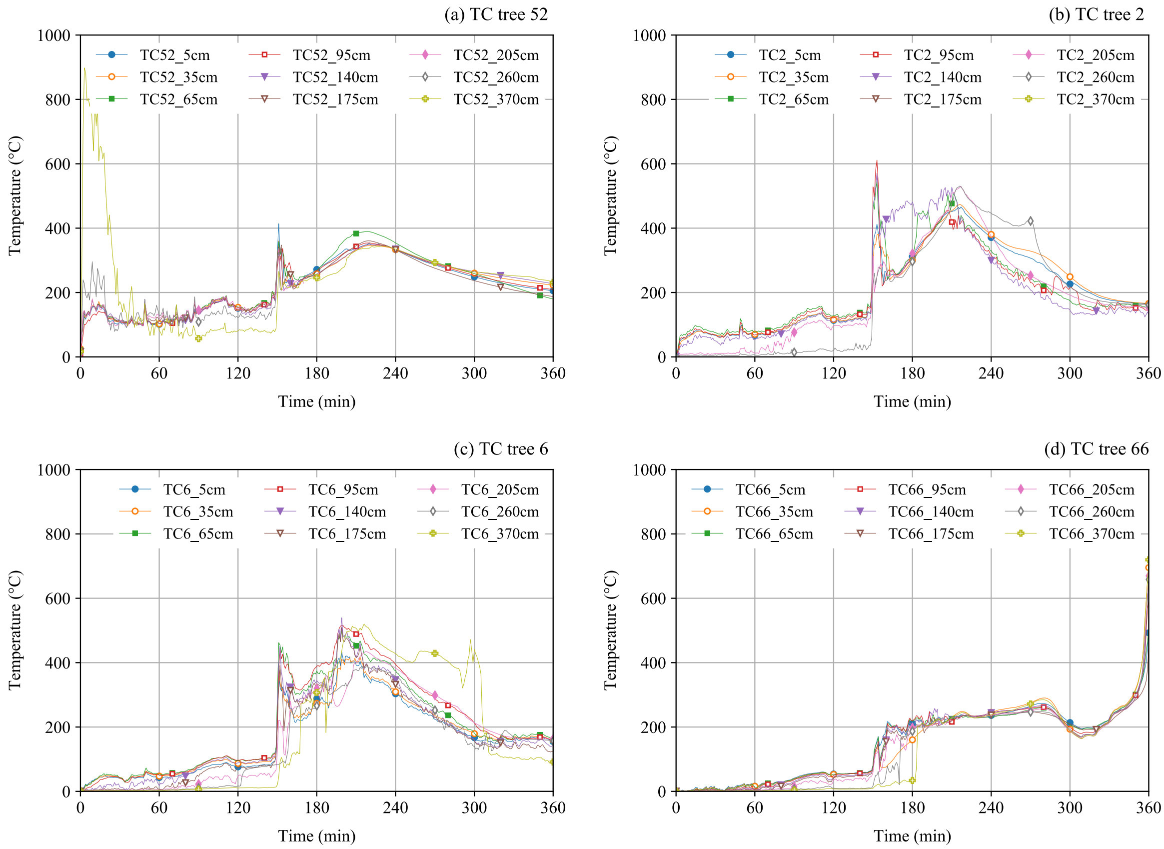


Figure 16. Temperatures of thermocouples at selected locations (a) TC tree 52 near the fire ignition location, (b) TC tree 2 at the intersection of Slice 1 and Slice 2, (c) TC tree 6 near the intersection of Slice 2 and Slice 3, and (d) TC tree 66 at the intersection of Slice 3 and Slice 4. (Exact TC tree locations can be found in Figure 3; distances are measured from the concrete slab soffit and to each TC location)

In Figure 16 (c), from 210 mins to 320 mins, the thermocouple near the fuel bed (i.e. 370 cm) had a higher temperature compared with the rest of the thermocouple temperatures on the tree. It is in line with the findings from Figure 11 (g) and Figure 13 (c). Again, this is mainly due to the 'burnt' fuel bed, which was remaining hot and less affected by the cold air through the openings due to the sill height. Figure 16 (d) presents the thermocouple tree 66 (located at the intersection of Slice 3 and Slice 4), which could be considered to be in the far-field under the travelling fire concept. Generally, the thermocouple temperatures were well below 300 ºC for the entire fire test duration from 0 min to 330 mins, except when the fire further travelled to the far-field region after around 330 mins which resulted in a high temperature increase. In addition, before Mode 1 launched from 0 min to 150 mins, the temperature near the ceiling has higher temperatures compared with the ones near the fuel bed. This is a result of the smoke layer development over time. Further, a transition stage happened from 150 mins to 180 mins, when the smoke accumulating to the full height of the compartment after the Mode 1 launched. After this time period, the far-field shared very similar temperature histories through the whole compartment height.

4 LESSONS LEARNT FROM THE EXPERIMENT

This experiment not only has provided some valuable experimental data but taught the team that set the experiment many valuable lessons with regards to both the nature of compartments and instrumentation for travelling fires.

Three interacting factors led to a longer than planned for burning time for the fire. The first was the wood moisture content as provided compared to as specified. The wood was specified to be 11% by mass moisture content, however, control specimens that were weighed and dried after the experiment found the moisture content to be between 18-22%. Higher moisture contents result in more energy being absorbed in the evaporation of water rather than into the fire environment and reduces the rate of flame spread [30–32].

The lack of energy being released in the fire environment were further exacerbated by the clear ceiling height (from the top of the wood crib to the soffit of the slab) and the ventilation; the clear ceiling height was roughly 4m and was too high to significantly impact the fire spread due to radiation feedback from the accumulated smoke layer; and the initial ventilation condition was to have all the windows open, to ensure that it was a fuel controlled fire, however, the initial spread rate was very slow, so approximately 1 hr into the experiment some of the ventilation was closed and a modest impact on temperatures and spread rate were seen.

Another potential factor on the spread rate could have been the weather conditions at the time of the experiment. The external temperatures on the day of the test were recorded between -3 – 0 °C, with winds 7 – 26 km/h and humidity between 80 and 93% [33]. Cold air and humidity could have contributed to the reduced severity of the initiating fire, and thus the spread rates. In tests on different fuels, flame spread rate and heat generation where found to be closely related to the absolute humidity, and being impacted by the initial environmental temperatures [34,35].

In terms of data, there were two things that, if changed, would have improved the overall quality of the data gathered. Firstly, removing the light fittings near the ceilings. These fittings (plastics mainly) placed combustible materials within the smoke layer near the soffits of the slabs and produced unintended data due to the fittings burning. Through looking through video footage, these erroneous data points were able to be removed. The second change would be to increase the protection of the thermocouple trees within the gas phase. The long duration of the fire, and in particular the long preheating phase of the first 150 minutes of the fire, lead to the thermocouple trees near the ignition point of the fire failing once the Mode 1 fire occurred.

5 FURTHER IMPLICATIONS TO THE TRAVELLING FIRE CONCEPT

Based on the findings in this test, it is worth revisiting the travelling fire concept to identify potential further recommendations. Three main theoretical representations of travelling fire concept can be found in the current literature, hereinafter referred to as: Clifton's model [36]; Rein's model [8,9,37]; and an extended travelling fire method (ETFM) framework [38]. Clifton developed a pioneer travelling fire model, which divides the whole large compartment into several design areas, which are then subjected to time-temperature curves individually and sequentially. In Rein's model, Alpert's correlation is adopted to calculate far field smoke temperature, and a uniform temperature (800 °C - 1200 °C) is assumed for the near field. The ETFM framework is developed by 'mobilising' Hasemi's localized fire model [39] for the fire plume near the structure, and combined with a simple smoke layer calculation by utilising a zone model [40] for the areas of the compartment away from the fire. However, all three models potentially neglect some aspects of the fire dynamics, which were identified in the Tisova Fire Test.

Firstly, it is found that the fire spread rate was highly non-uniform during the test (see Figure 5 and Figure 7). The spread rates were strongly affected by two factors: the relative locations between the burning fuel bed and the openings, and the wood stick moisture inside. In addition, the inclusion of the accelerant during the test brings in another factor which affects the fire spread drastically. However, the current travelling fire models use predefined constant fire spread rates which might oversimplify the problem, except Hopkin [41] attempted to improve Rein's model to put a connection with the fire spread rate with a t^2 fire. Secondly, the temperature of the travelling fire near-field, as well as the flashover region, the maximum was around 600 °C near the ceiling level (see Figure 12 and Figure 16). Thirdly, smoke layer accumulation was identified in the test, including the initial formation of the two-zone distinct temperature layers, and subsequent transition to one single zone after Mode 1 fire launched. Finally, all the three travelling fire models are specially designed for horizontal structural elements (i.e. beams and slabs), there are no corresponding travelling fire methodologies developed for vertical structural members (i.e. columns).

Other work by Hidalgo et al. [25] identifies different *Modes* based on spread rate and burnout rate that can be used to characterise fires in open plan compartments. Based on an analysis of the spread and burnout rates in the Tisova tests, all four of these modes can be identified and their impact on the temperatures recorded throughout the compartment is clear. The impact of ventilation on the Mode is also demonstrated, in the transition from Mode 3 to Mode 2. These Modes suggest that the fire dynamics implied in the models cited above may need to account for variable spread and burnout rates driven by other features in the compartment – assuming constant spread and burnout rates does not accurately reflect the range of behaviours possible.

6 CONCLUSIONS

This paper has presented experimental results of the Tisova fire test, conducted in the Czech Republic in January 2015. The fire displayed clearly travelling behaviour, although the flame spread rate was very slow in the early part of the test. In response to this slow spread of fire it was decided during the test to add a mixture of diesel and gasoline to the fuel bed below slabs S1 and S2. This of course affected the fire dynamics inside of the compartment, contributing to a significant increase in fire spread rate (approx. 8 mm/s) and subsequently temperatures inside of the compartment. The influence of the diesel / gasoline mixture was only significant for the period when the fire was beneath slabs S1 and S2 and the flame spread rate reduced significantly when the fire spread to slab S4. The high temperatures failed in this instance to significantly pre-heat the fuel bed in front of the fire.

The development of temperatures in the far field is very clear during the test, with a significant drop off in temperature with increasing distance from the location of burning in the compartment. Far field temperatures are observed only to influence the upper layers of the compartment.

The temperatures in the near field are significantly higher than those in the far field. Temperature profile with depth in the near field is largely either uniform, based on the thermocouple measurements, or in fact is higher closer to the floor. This has potential implications with regards to the design of vertical elements for travelling fires.

On reflection, the fire test was subject to a great number of issues with regards to the test setup and the compartment configuration. Not least of all was the high moisture content of the timber which was used as fuel for the test. This led to significantly lower flame spread rate (< 1 mm/s) than would have been expected had the fuel been dry. It is also possible that different configuration of fuel load would have contributed to a faster flame spread – with a larger surface area resulting in faster burning rate of the wood. Nevertheless, it could be expected that the high ceiling heights, coupled with open windows and a stiff breeze on the day of the test could contribute to a slow development of far field or upper layer temperatures. This would also have contributed to a slower than desired spread of flame within the compartment by preventing or limiting the preheating of the fuel bed by the hotter upper layer throughout the building since this was not able to develop.

The significant duration of the fire also had implications for the survivability of the thermocouples. Had the fire been shorter than the insulation material around the shielded thermocouples wires which were in the compartment would have been likely to provide adequate protection from the effects of heating. This would have prevented problems with data capture.

In conclusion, whilst this experiment did not go fully as intended, a lot of significant understanding and data has been obtained and many lessons learnt that others could use to ensure their own experiments do not fall to the same issues as experienced here.

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REFERENCES

[1] D. Martin, D. Moore, Introduction and background to the Research Programme and Major Fire Tests at BRE Cardington., in: Natl. Steel Constr. Conf., 1997.

[2] CEN, BS EN 1991-1-2:2002 Eurocode 1- Actions on structures; Part 1-2: General Actions - Actions on structures exposed to fire, Brussels, Belgium, 2009.

[3] J. Gales, C. Maluk, L. Bisby, Large- scale structural fire testing- How did we get here, Where are we, and where are we going?, in: 15th ICEM, Porto, Portugal, 2012: pp. 1–22. http://www.era.lib.ed.ac.uk/handle/1842/6176 (accessed May 24, 2014).

[4] NIST, Federal Building and Fire Safety Inverstigation of the World Trade Centre Disaster: Final Report on the Collapse of the World Trade Center Towers, Gaithersburg, MD, 2005. http://www.nist.gov/customcf/get_pdf.cfm?pub_id=861610.

[5] NIST, Final Report on the Collapse of World Trade Center Building 7, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Gaithesburg, MD, 2008.

[6] I.A. Fletcher, A. Borg, N. Hitchen, S. Welch, Performance of concrete in fire: A state of the art, with a case study of the Windsor Tower fire, in: 4th Int. Work. Struct. Fire, 2006: pp. 779–790.

[7] B. Meacham, H. Park, M. Engelhardt, A. Kirk, V. Kodur, I.J. Straalen, J. Maljaars, K. van Weeren, R. de Feijter, K. Both, Fire and Collapse , Faculty of Architecture Building , Delft University of Technology : Data Collection and Preliminary Analyses, in: 8th Int. Conf. Performance-Based Codes Saf. Des. Methods, Lund, Sweden, 2010.

[8] J. Stern-Gottfried, G. Rein, Travelling fires for structural design-Part II: Design methodology, in: Fire Saf. J., 2012: pp. 96–112. doi:10.1016/j.firesaf.2012.06.011.

[9] E. Rackauskaite, C. Hamel, A. Law, G. Rein, Improved formulation of travelling fires and application to concrete and steel structures, Structures. 3 (2015) 250–260. doi:10.1016/j.istruc.2015.06.001.

[10] X. Dai, Extended travelling fire method framework with an OpenSees-based integrated tool SIFBuilder, Univeristy of Edinburgh, 2018.

[11] J. Stern-Gottfried, G. Rein, Travelling fires for structural design–Part I: Literature review, Fire Saf. J. 54 (2012) 74–85. doi:10.1016/j.firesaf.2012.06.003.

[12] X. Dai, S. Welch, A. Usmani, A critical review of "travelling fire" scenarios for performance-based structural engineering, Fire Saf. J. 91 (2017) 568–578. doi:10.1016/j.firesaf.2017.04.001.

[13] D. Rush, D. Lange, Towards a fragility assessment of a concrete column exposed to a real fire – Tisova Fire Test, Eng. Struct. 150 (2017) 537–549. doi:10.1016/j.engstruct.2017.07.071.

[14] J. Gales, Travelling Fires and the St. Lawrence Burns Project, Fire Technol. 50 (2014) 1535–1543.

doi:10.1007/s10694-013-0372-3.

[15] B.R. Kirby, D.E. Wainman, L.N. Tomlinson, T.R. Kay, B.N. Peacock, NATURAL FIRES IN LARGE SCALE COMPARTMENTS, Int. J. Eng. Performance-Based Fire Codes. 1 (1999) 43–58.

[16] British Steel Plc, The behaviour of multi storey steel framed building in fire, 1999.

[17] T. Lennon, D. Moore, The natural fire safety concept - full-scale tests at Cardington, Fire Saf. J. 38 (2003) 623–643. doi:10.1016/S0379-7112(03)00028-6.

[18] S. Welch, A. Jowsey, S. Deeny, R. Morgan, J.L. Torero, BRE large compartment fire tests-Characterising post-flashover fires for model validation, Fire Saf. J. 42 (2007) 548–567. doi:10.1016/j.firesaf.2007.04.002.

[19] D. Joyeux, J. Kruppa, L.G. Cajot, J.B. Schleich, P. Van de Leur, L. Twilt, Demonstration of real fire tests in car parks and high buildings, 2002.

[20] I. Thomas, K. Moinuddin, I. Bennetts, Fire development in a deep enclosure, in: Fire Saf. Sci. - Proc. 8th Int. Symp., 2005: pp. 1277–1288. doi:10.3801/IAFSS.FSS.8-1277.

[21] L. Simões da Silva et al., Design of Composite Joints for Improved Fire Robustness (Compfire) - Final Report, Luxembourg, 2014.

[22] J.L. Torero, A.H. Majdalani, C. Abecassis Empis, A. Cowlard, Revisiting the compartment fire, in: 11th Int. Symp. Fire Saf. Sci., International Association for Fire Safety Science, Christchurch, New-Zealand, 2014.

[23] C. Maluk, B. Linnan, A. Wong, J.P. Hidalgo, J.L. Torero, C. Abecassis-Empis, A. Cowlard, Energy distribution analysis in full-scale open floor plan enclosure fires, Fire Saf. J. (2017). doi:10.1016/j.firesaf.2017.04.004.

[24] J.P. Hidalgo, A. Cowlard, C. Abecassis-Empis, C. Maluk, A.H. Majdalani, S. Kahrmann, R. Hilditch, M. Krajcovic, J.L. Torero, An experimental study of full-scale open floor plan enclosure fires, Fire Saf. J. 89 (2017) 22–40. doi:10.1016/j.firesaf.2017.02.002.

[25] J.P. Hidalgo, T. Goode, V. Gupta, A. Cowlard, C. Abecassis-Empis, J. Maclean, A.I. Bartlett, C. Maluk, J.M. Montalvá, A.F. Osorio, J.L. Torero, The Malveira fire test: Full-scale demonstration of fire modes in open-plan compartments, Fire Saf. J. (2019). doi:10.1016/j.firesaf.2019.102827.

[26] J. Degler, A. Eliasson, J. Anderson, D. Lange, D. Rush, A-priori modelling of the Tisova Fire Test as input to the experimental work, in: First Int. Conf. Struct. Saf. under Fire Blast,Glasgow, Scotland, UK, 2015: pp. 429–438.

[27] D. Lange, D. Rush, X. Dai, L. Boström, D. Lange, D. Rush, X. Dai, The Tisova fire test part 1 : test report, 2018.

[28] D. Lange, D. Rush, L. Boström, A. Byström, K. Olsson, Z. Triantafyllidis, The Tisova fire test part 2 : heat transfer analysis, 2018.

[29] D. Rush, X. Dai, D. Lange, Tisova Fire Test Data, (2020). doi:10.7488/ds/2844.

[30] J. Quintiere, Principles of fire behavior, CRC Press, 2016.

[31] W.L. Fons, H.B. Clements, P.M. George, Scale effects on propagation rate of laboratory crib fires, Symp. Combust. 9 (1963) 860–866. doi:10.1016/S0082-0784(63)80092-2.

[32] H.P. Steinhagen, Thermal conductive properties of wood, green or dry, from-40ºC to +100ºC: a literature review., US Prod Lab Gen Tech Rep FPL-9. (1977).

[33] Tisova - Daily weather history, (n.d.). https://freemeteo.mn/weather/tisova/history/daily-history/?gid=3064206&station=3966&date=2015-01-30&language=english&country=czech-republic (accessed March 2, 2019).

[34] G. Keshavarz, F. Khan, K. Hawboldt, Modeling of pool fires in cold regions, Fire Saf. J. 48 (2012) 1–10. doi:10.1016/j.firesaf.2011.11.003.

[35] M. Suzuki, H. Kushida, R. Dobashi, T. Hirano, Effects of Humidity and Temperature on Downward Flame Spread over Filter Paper, (n.d.).

[36] C.G. Clifton, Fire Models for Large Firecells. HERA Report R4-83, 1996.

[37] G. Rein, X. Zhang, P. Williams, B. Hume, A. Heise, A. Jowsey, B. Lane, J.L. Torero, Multi-storey fire analysis for high-rise buildings, in: Proc. 11th Int. Interflam Conf. London, UK, London, UK, 2007: pp. 605–616.

[38] X. Dai, S. Welch, O. Vassart, K. Cábová, L. Jiang, J. Maclean, C.G. Clifton, A. Usmani, An extended travelling fire method framework for performance-based structural design., 44 (2020) 437–457. doi:10.1002/fam.2810.

[39] Y. Hasemi, Y. Yokobayashi, T. Wakamatsu, A. V. Ptchelintsev, Modelling of heating mechanism and thermal response of structural components exposed to localised fires, Thirteen. Meet. UJNR Planel Fire Res. Saf. (1996) 237–247.

[40] M.L. Janssens, An Introduction to Mathematical Fire Modeling, 2nd ed., CRC Press, 2000.

[41] D.J. Hopkin, Testing the single zone structural fire design hypothesis, in: 13th Int. Fire Sci. Eng. Conf. (Interflam 2013), London, UK, 2013: pp. 139–150.